Solar System Visualization:

Global Science Maps

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Abstract

The goal of the Solar System Visualization (SSV) project is tore-explore the planets using the data from previous National Aeronautics and Space Administration (NASA) planetary missions and to create new materials for science, education and public information. Major products from this activity include a series of Global Science Maps (GSM), videos and interactive CD-ROMs for each planet in the solar system, These products will display:

(a) time dependent planetary phenomenon,
(b) high resolution mosaics of surfaces,
(c) perspective views of three-dimensional topography,
(d) a visual image catalog of surfaces, atmospheres and rings.

Examining, organizing, processing and presenting images of surfaces and atmospheres is a fundamental problem in space science. Current systems provide the ability to process planetary data into individual images, but are limited in their ability to provide interactive access to large variable-resolution 2-D and 3-D global maps. The SSV project is creating an interactive system for scientists which provides the ability to create Global Science Maps, The system will allow scientists to continuously control the position, flight path and motion of a set of virtual cameras. The cameras will provide three-dimensional perspective views or time-lapse sequences of global maps and regions.

The maps arc constructed from mosaics of variable-resolution planetary images. Perspective viewing provides a natural viewing geometry for identifying and comparing planetary features. Time-lapse sequences provide a natural technique for viewing atmospheric dynamics. The processing steps and virtual camera motion control executed by the scient ist will be saved by the interactive system so that the same views could be used in benchmarks and scientific presentations and shared with colleagues and students. This paper discusses the current state of the SSV project and provides some examples of work in progress.

Previous Work

Over the last thirty years a number of systems have been developed to assist scientists in analyzing individual images and pairs of images. The most widely used of these is the Video Image Communicant ion and Retrieval (VICAR) program developed at Jet Propulsion Laboratory's (JPL) Multimission image Processing laboratory (MIPI ,), VICAR is the primary analysis package used for NASA planetary science missions. VICAR includes contributions from scient ists throughout NASA and the academic communities. JPL's image Processing Applications and Development Section has been a pioneer in the development of image processing and visualization software for Planetary and Earth Science applications. The VICAR image processing library contains over 250 programs developed by J]']. and contributing scientists for the processing of planetary images. included in this library are programs to: (1) navigate images to determine planetary coordinates, (2) compute and correct for photometric functions to produce, calibrated uniformly illuminated images, (3) transform images using a variety of map projections, and (4) mosaic map projected images together to produce global maps, 'l'he complete VICAR library will also be available on Unix systems sometime in the next few years. The Planetary Image Cartographic System (PICS) developed by the United States Geological Survey will also be available on Unix systems in the same time frame. This will greatly increase the access to VICAR and PICS by the science community. Some VICAR and PICS map projection programs arc already available on Unix workstations.

In ,1986, the JPL Visualization & Earth Science Applications (VESA) group began the development of a series of visualization tools designed for Earth Science applications. These tools include ray casting programs which render realistic three-dimensional perspective views of surfaces from image and topographic data. The 3DI program enabled the user to define a sequence of perspective viewing points. 3DI can be used to define a flight path through three-dimensional space. Unfortunately, 3DI required the user to input a large number of parameters and runs only on machines with a VMS operating system, 3DI is a prototype system, and is somewhat difficult to use. A new program called Surveyor has been under development for the last few years to replace 3DI. Surveyor is designed to run an Unix workstations. Both 3DI and Surveyor have been used by their developers to produce several successful experimental scientific visualizations. 3DI was used to produce "LA the Movie" and "Mars the Movie" and Surveyor to produce "Monterey the Bay." In this same time frame, members of the JPL Image Analysis Systems (IAS) group were experimenting with science analysis and visualization algorithms on a Concurrent Image Processing Testbed (CIPT).

Solar System Visualization Project, the beginning

The Solar System Visualization (SSV) project began with the Neptune Encounter. On August 25, 1989, the Voyager 2 spacecraft approached to within 4400 kilometers of the top of Neptune's atmosphere. The encounter with Neptune completed Voyager's Grand Tour of the outer solar system. The science community and the public were intensely interested in this outermost of the gas giants and its mysterious retrograde moon, Triton. During the months prior to the closest approach, a few scientists from the Voyager imaging team, in collaboration with MIPL, IAS and DIAL personnel, tied the three labs together through a high-speed network to form a visualization pipeline. This team of scientists and technologists worked together to develop new visualization and analysis algorithms specifically for the Neptune Encounter. Nine visualization segments were created using the new algorithms in the few weeks surrounding the encounter. Figure 1 is one of the 29 high resolution images of Neptune's Great Dark Spot (GDS) used to create a "feature locked" animation of this storm system. in the animation, the images are "feature locked" so that the observer moves in a reference frame which is fixed at the center of the GDS. in this way, the motion of the GDS about its own center is easily observed, This animation of the GDS provided the first indication of the anticyclonic motion of the GDS and the first measure of its rotation period.

The team of scientists and technologists continued to work together after the Neptune encounter and the SSV project was born, The team produced a series of animations entitled "The Voyager Science Summary" using the Voyager data set, Figure 2 shows another use of "feature locking" Figure 2 is a single frame from an animation which compares the view of Jupiter's Great Red Spot as seen by the Voyager 1 spacecraft with a view of the same area three months later as imaged by the Voyager 2 spacecraft, The SSV team has continued to adapt elements of 3DI, VICAR, PICS and commercial software and develop new algorithms to create a series of scientific visualizations of planetary surfaces and atmospheres. The SSV project plans to extend these early experiments, and utilize key elements of 3DI, VICAR, PICS and Surveyor to produce a system which provides scientist controlled virtual cameras for: (1) three-dimensional perspective viewing of large variable resolution mosaics, and (2) "feature locked" time lapse images of atmospheric motion, The system will use a global coordinate system with several different rendering algorithms to provide for speed and quality tradeoffs.

Scientific objectives

The SSV project plans to create a set of scientist controlled virtual cameras (SCVC). The SCVC will allow scientists to organize and view planetary image data as sequences of global maps. Organizing, examining, and providing a complete scientific analysis of the images recorded by a spacecraft is a fundamental problem in space science. Understanding planetary surfaces and atmospheres requires a global view of the surface classification, topography and atmospheric dynamics, along with detailed studies of small-scale features and feature dynamics. The challenge of obtaining a degree of understanding of the basic physical processes at work is complicated by the need to compare this data with data from computer models and from other planetary missions. Thirty years of highly successful planetary missions have provided data for a large number of planetary images. Most of these images have been viewed by only a handful of people.. The data has been stored as single wavelength unprocessed images on magnetic tape. Recently, some of the data has been transferred to CD-ROM.

Global maps provide order and context while the. virtual caroms provide a natural interface for conducting scientific investigations. The intent is to enhance the capabilities inherent in visualization software developed at JPL and the USGS, and to host the resulting software on a system which is compatible with the Home institution Image Processing Systems (} HIPS), the Space operations Planning Computers (SOPC) and other systems readily accessible to most scientists.

Spacecraft imaging and camera systems produce multi-spectral planetary image frames which vary in size and resolution. Each frame contains planetary images which vary in size and position within the frame. These variations are due to differences in planetary size, range, spacecraft pointing, focal length and imaging system characteristics. Frames taken at a great distance from the planet will contain only a few pixels for the image of the planet. Frames taken at closest approach may contain images of the planet which fill the entire frame. A typical planetary mission will produce between ten thousand and one hundred thousand image frames. in addition to the imaging data, radiometric and topographic data may also be available. The latter may be measured by other spacecraft instruments or derived from photogrammet ry, photoclinomet ry, or spectral analysis.

The frames have a natural order based on exposure time and spectral band. The images may also be organized according to their positions expressed in planetary coordinates, The creat ion of global maps and mosaics is a natural method for organizing the images based on planetary coordinates. Sequences of mosaics ordered either by time or spectral band will then provide an orderly progression through the image data. Color may be used to combine data from multiple spectral bands. Perspective views may be used to simultaneously display radiometric or topographic data with the imaging data on a display surface. Examination of the resulting data requires that a scientist be able to control a time sequence of perspective viewpoints in a global coordinate system to provide the appropriate image presentation.

The sequence of global maps described above is the natural way to view planetary surfaces and atmospheres. Displaying high resolution maps on a workstation with image pan and zoom capability is the ideal method for presenting this data. The production of mosaics requires considerable knowledge about the instrument and the mission, Fortunately, the Regional Planetary imaging Facility (RPIF), Data Restoration task, and Planetary Data System (PDS) arc preserving this critical mission information, The SSV team is developing a series of high resolution global maps in collaboration with NASA flight project teams, The development of these maps and the scientist virtual camera will greatly aid in the planning of current and future solar system exploration missions.

Scientist Controlled Virtual Camera (SCVC) Design Issues

The SSV project intends to develop the. SCVC in a machine-independent fashion to provide maximum accessibility to the science community. The user interface will first be developed on a Silicon Graphics indigo-]1 workstation using the Unix operating system, Motif and X-Windows. Motif and X-Windows will provide a standard display environment which is supported on many different computer systems. We will concentrate. on providing an implementation on a Silicon Graphics workstation, but wc will also experiment with implementation on the SPARC-10 workstations, The development of the SCVC on a scientific workstation requires several specialized component S. The first is hardware. A large frame buffer provides the ability to hold a large single mosaic or large number of individual map-projected images, A digital optical disk allows the program to access even larger collections of images although at lower speed than for images in memory. A high speed image processing board provides speedup of the comput at ions and can provide hardware pan and zoom capability for 2D real time motion. A joystick, trackball, spaceball or glove provides the user with easy control of the motion and orientation of the virtual camera, We intend to provide a stereo display capability, creating one image for each eye. The software will calculate the correct view for each eye from a single flight path,

The second component is the display and interface software. "l'here are several ways to render an image of a surface or three-dimensional object. These renderers produce different displays of the object. 'l'he simplest renderers produce wire frame representations of the outline of surfaces. More complicated renderers produce shaded facet representat ions of the surfaces; 'l'he best renderers use geometric optics to trace rays and provide the most realistic representation of the surfaces. A hierarchy of renderer is u seful so that the best renderer may bc selected for a given applicat ion. Wire frames are computations] 1 y the least expensive and can be implemented on low-cost workstations to allow the scientist to play with the camera trajectory and pointing in near real time. once a trajectory is selected, the slower but more realistic renderers may be. used to produce final products.

The third component is the data structure. Storing the same image at several different resolutions in a multiresolution pyramidal data structure can reduce the computational requirements on the renderer by using lower resolution images for elements of the scene that arc far from the camera or are blurred by camera motion. It is not necessary or desirable to register and mosaic all of the data into one large data set. For instance, the resolution, illumination and viewing angles may change, and different overlapping images of the same area may satisfy different imaging objectives. It is only necessary to map-project the images into a standardized global coordinate system to support three-dimensional perspective rendering on any portion of the original data. Where data sets overlap, the images arc blended (composited) following rules chosen by the user.

Global Science Maps

Global Science Maps (GSM) arc being created for all planets and satellites for which we have data. 'l'he size of the mosaics can bc expressed as the number of lines and samples in the mosaic. For each line-sample location, 8 bits of storage arc required for each filter bane] represented. Digital Elevation Maps (DEM) registered to the image maps require a minimum of 16 bits of storage for each location. Often elevat ion information is onl y avai lable at lower resolution than the image data, '1'bus, a single 1000 by 4000 three-band (color) mosaic of Jupiter will require 12 megabytes of storage. For case of comparison, approximate numbers arc used in the table below (for example, the correct size for the 2.()() Jupiter mosaics is 965 lines of 3915 samples each, where the approximate value used in the table is 1()()() * 4000). Some examples of the GSMs being created arc given in the table below:

Description of Mosaics	Number of Lines* Number of Samples
• 200 global mosaics showing daily variations in Jupiter's atmosphere.	1000 * 4000
• 100 Jupiter images of widely varying resolution.	1000 * 4000
• 30 variable resolution images of Neptune's Great Dark Spot.	800 * 800
• 1 global mosaic of Triton using images of widely varying resolution.	5000 * 5000
• 1 global mosaic of Venus (Magellan SAR) with lower resolution topography.	7000 * 16000
• 1 global map of Mars with topography for selected portions,	1 2000* 23000
• 365 * 12 daily global low resolution maps of the Earth's ozone.	400 * 400
• 1 variable resolution map of the coastal regions of California	1 2000* 15000

Visualization of Venus using Magellan Synthetic Aperture Radar (SAR) Images:

One of the most complete planetary global science maps is that which has been provided by the Magellan radar mapping mission to Venus, For the past three years, the Magellan spacecraft has mapped over 99% of the surface of Venus, using a s ynthet ic aperture rad ars ystem to penetrate the dense atmosphere of Venus. Figure 3 describes the steps required to process Magellan's radar signal and construct image mosaics and global mapping products.

Figure 4 is an image mosaic of a portion of Western 1 Eistla Regio. Overlayed on the radar image is a blue line defining the eyepoint and look position, with two green lines defining the field of view of our virtual camera system (the red rectangle defines the data used to create the three-dimensional view). in Figure 5, we see a three-dimensional perspective view of this same region rendered in the computer using a ray casting program. The viewpoint is located 725 kilometers (450 miles) southeast of Gula Mons at an elevation of 1.2 kilometers (().74 miles). Magellan synthetic aperture radar data is combined with radar altimetry to develop a three-dimensional map of the surface. Ray casting is used to generate a perspective view from this map. The vertical scale is exaggerated approximately 23 times, Simulated color and a digital elevation map developed by the U.S. Geological Survey are used to enhance the small scale structure. The simulated hues are based on color images recorded by the Soviet Venera 13 and 14 spacecraft.

in Figure 6, we see a portion of Leda Planitia. This image illustrates the basic stratigraphy of Venus. The oldest terrains appear as bright highly fractured highlands rising out of the plains. The circular ring struct ure is probabl y an impact crater formed before the plains lava embayed and covered the region, 'l'he most recent activity in the region is volcanism that produced the radar bright flows seen in the upper right quadrant of the image.

Supporting Facilities

The work discussed in this paper uses (he computational and networking facilities at Caltech and JPL. Algorithm development and demonstration was carried out utilizing the Multi mission

Image Processing Laboratory (MIPL) VAX computer cluster and the Digital Image Animation Laboratory (DIAL) science workstations at JPL. The DIAL has twenty Sol bourne (SPARC-10 compatible) processors, along with special purpose video animation equipment and several image/graphics display processors. MIPL and the DIAL are operated as sub-nets of the JPL Intralaboratory Local Area Network (LAN), which in turn provides gateway service to the Caltech CITNET, and the NASA Science Network. The Caltech CITNET was used to provide connection to the Division of Geological and Planetary Science Computing Facility. This facility provides individual Silicon Graphics, SPARC- 10 and MicroVAX science workstations connected to the Caltech VAX hypercube cluster. This capability will be used to support the work carried out under this proposal. The Concurrent image Processing Testbed is also connected to the network and provided additional image processing applications software.

Acknowledgements

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Biographical Sketch

Dr. Eric M. De Jong is a Planetary Scientist with the Earth and Space Sciences Division of the NASA Jet Propulsion Laboratory, and a Visiting institute Associate in the Division of Geological and Planetary Science, California institute of Technology, Eric is the principal investigator for the Solar System Visualization (SSV) project, a joint Caltech/JPL/USGS/University of Arizona research project. This project was selected by NASA as one of three NASA science projects featured at the World Space Congress for the International Space Year. Eric and the SSV team have produced animations and imaging products for the Magellan, Galileo, Voyager, Mars Observer and Ulysses projects. Eric is also the principal investigator for the Interactive Planetary Atlas (IPA) and Planetary Evolutionary Processes (PEP) projects.

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FIGURE CAPTIONS

Figure 1. nigh resolution image of Neptune's Great Dark Spot (GDS) used to create a "feature locked'' animation of this storm system. [JPL #P-34988]

Figure 2. Comparison of two views of Jupiter's Great Red Spot, as imaged by the Voyager 1 and Voyager 2 spacecraft, [J]']. # P-36749BC]

Figure 3. A description of the steps required to process Magellan's radar signal and construct image mosaics and global mapping products, [JPL # P-4 1959]

Figure 4, An image mosaic of a portion of Western Eistla Regio. The blue line defines the eyepoint and look position. Two green lines define the field of view of our virtual camera system, [JPL # 1'-39092]

Figure 5. A three-dimensional perspective view of the volcanic region displayed in Figure 4. The perspective view was rendered using a ray casting program, The vertical scale in the image has been exaggerated 10 times. Simulated color and a digital elevation map are used to enhance small scale structure, [JPL # P-382.1 8]

Figure 6. A portion of Leda Planitia, which illustrates the basic stratigraphy of Venus. The oldest terrains appear as bright highly fractured highlands rising out of the plains. [JPL # P-39659(3

Figure 7. Magellan radar data was used to create this three-dimensional perspective view of Maat Mons, an 8 kilometer (5 mile) high volcano. The vertical scale in the image has been exaggerated 10 times. Simulated color and a digital elevation map are used to enhance small scale. structure. [JPL # P-401 75]

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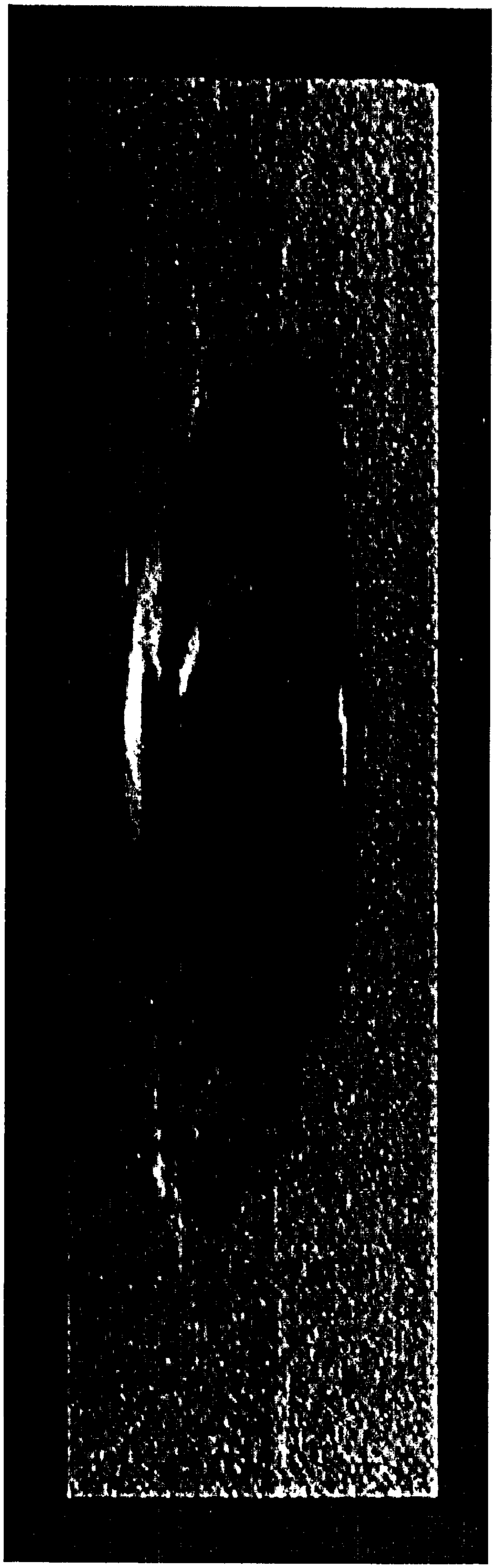

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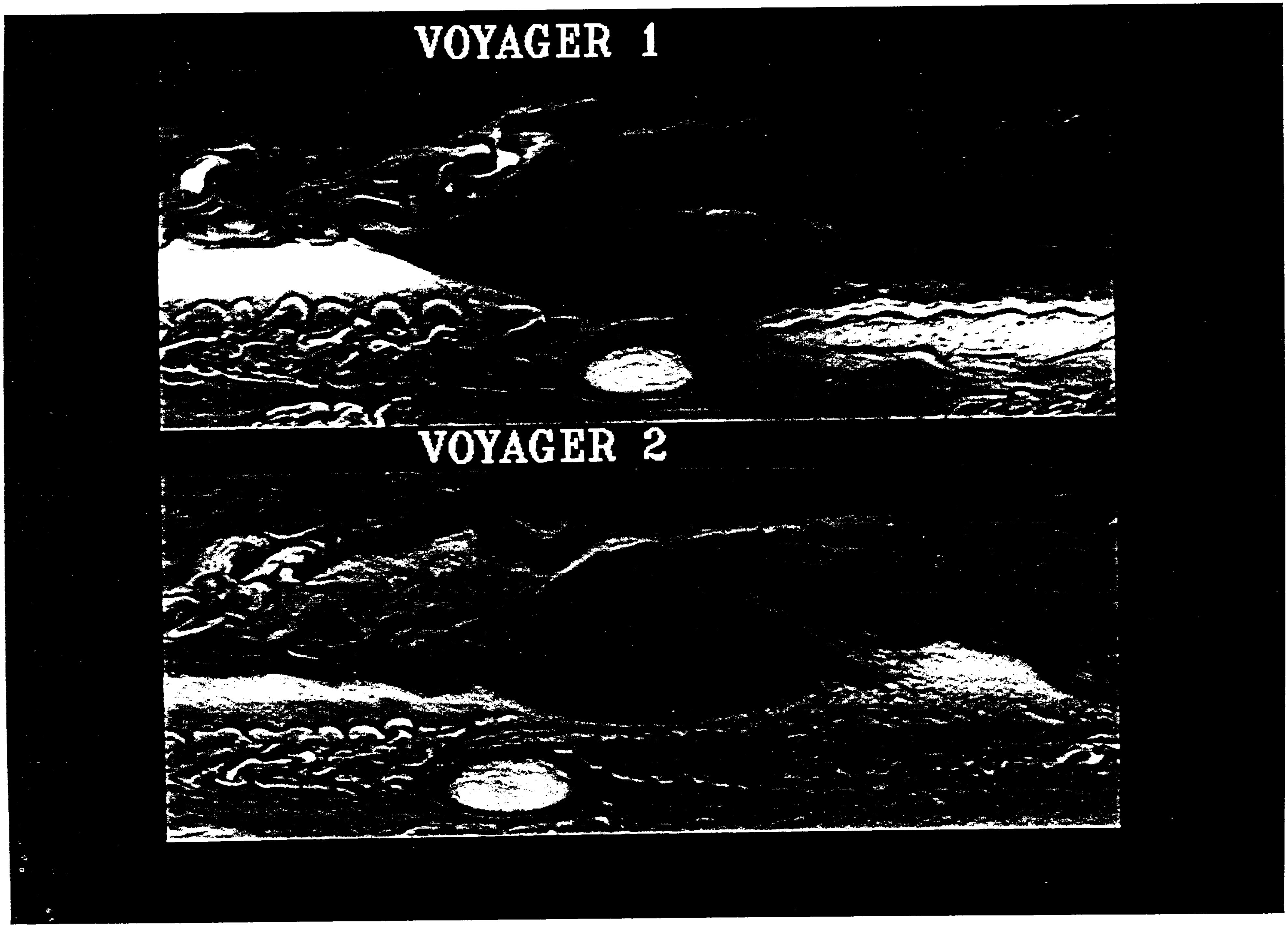
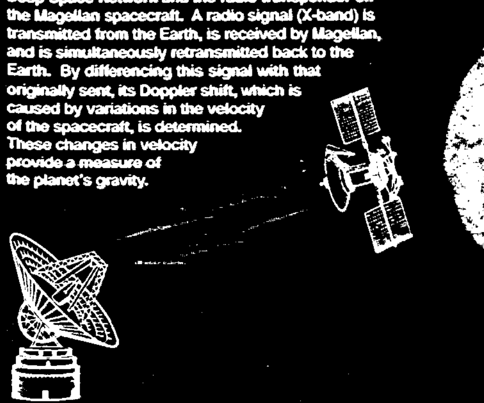
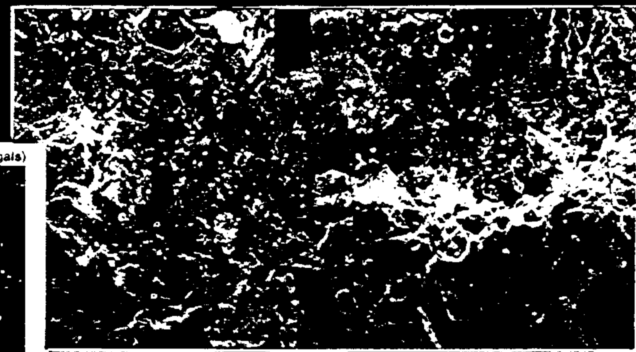




the Magellan spacecraft. A radio signal (X-band) is transmitted from the Earth, is received by Magellan, and is simultaneously retransmitted back to the Earth. By differencing this signal with that originally sent, its Doppler shift, which is caused by variations in the velocity of the spacecraft, is determined. These changes in velocity provide a measure of the planet's gravity.

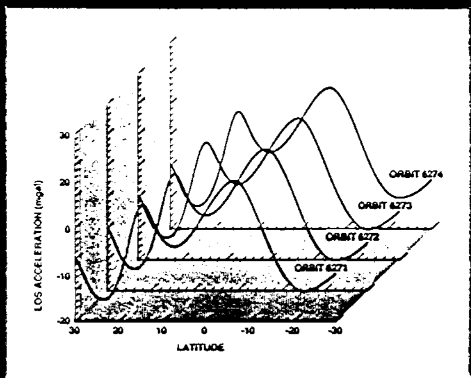
The first three cycles of the Magellan Mission to Venus were dedicated to collecting global radar-image and topographic data. In September, 1992, the Mission began its gravity data collection phase. By precisely tracking Magellan, small variations in the speed of the spacecraft as it orbits Venus are measured. These changes in speed, or accelerations observed along the line-of-sight (LOS) between Earth and Magellan, are caused by density variations within the planet. By combining gravity measurements with image and topographic data, a better understanding of the processes within the planet and their relationship to surface features is obtained.



Images from the first three mapping cycles are mosaicked, giving a global view of the planet. These data provide a basis for establishing a correspondence between surface geologic features and gravity.

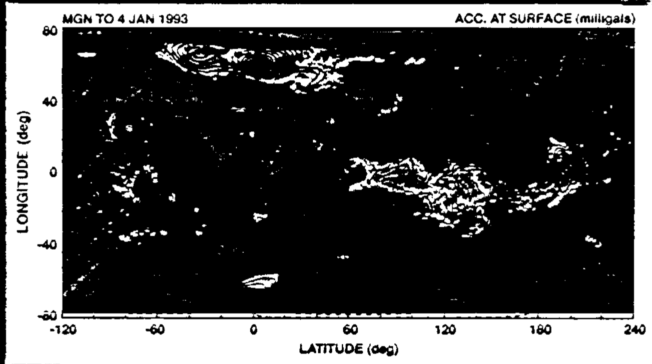
Data Processing

Magellan radio tracking observations, obtained along an orbit arc approximately 17,000-km-long, are processed at the Jet Propulsion Laboratory. To obtain the gravity signal due to surface and subsurface density variations, these data are processed to remove the effects from space plasma, solar radiation pressure, the Earth's atmosphere, the Earth's rotation, and the orbital motion of the spacecraft. By determining changes in the spacecraft's velocity via the Doppler shift of the radio signal, gravitational accelerations are obtained.

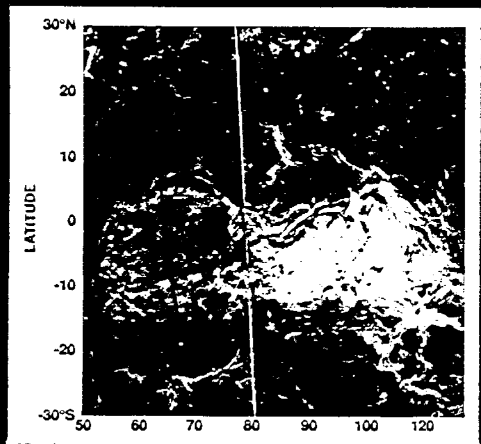


Magellan gravity data products consist of profiles of line-of-sight (LOS) accelerations of the spacecraft, measured in units of milligals (1×10^{-3} cm/sec^2), collected along each orbit. Shown here are a set of orbits that cover a section of the western part of Aphrodite Terra (Ovda Regio). The large gravity high corresponds to an elevated, radar-bright, complex ridged terrain (tesserae) seen in the image on the right. The smaller amplitude gravity high appears to correspond to a large volcanic center within the plains adjacent to Ovda Regio.

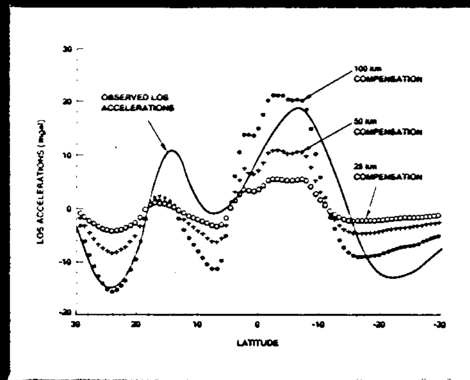
Venus Gravity: 60th Degree and Order



Radio tracking data from both Magellan and the Pioneer Venus Orbiter are combined to produce a high-resolution map of the Venus gravity field.



Magellan Orbit 6274



The observed gravity can be modeled by calculating the gravitational attraction due to the topography and to a corresponding compensating mass (a mass equal and opposite to that of the topography) at depth. On the basis of these results, along with information from the image data, an assessment is made as to the degree to which features on the surface are supported by crustal thickness variations or dynamic processes within the mantle.

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Figure 3 P-41959

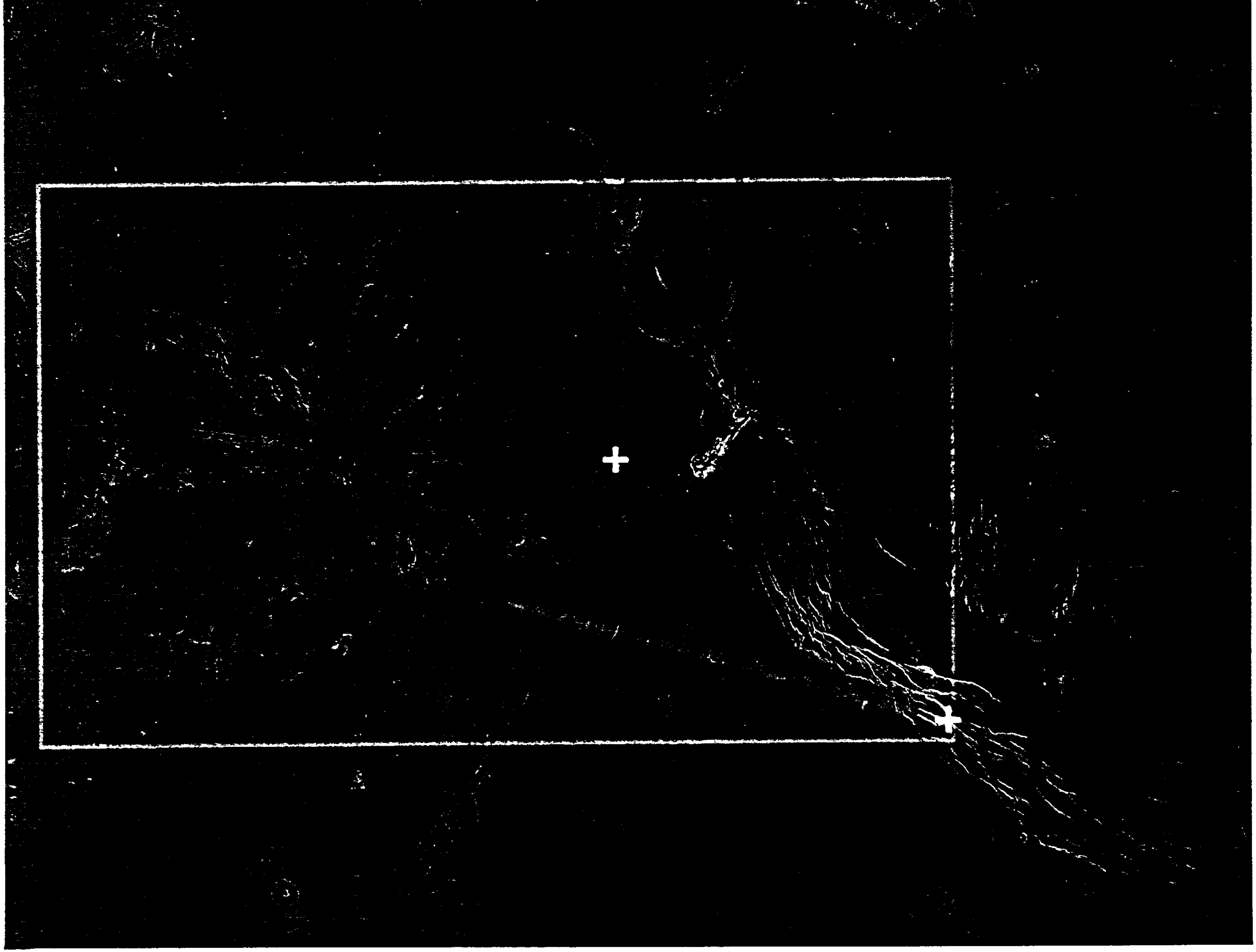

Figure 4
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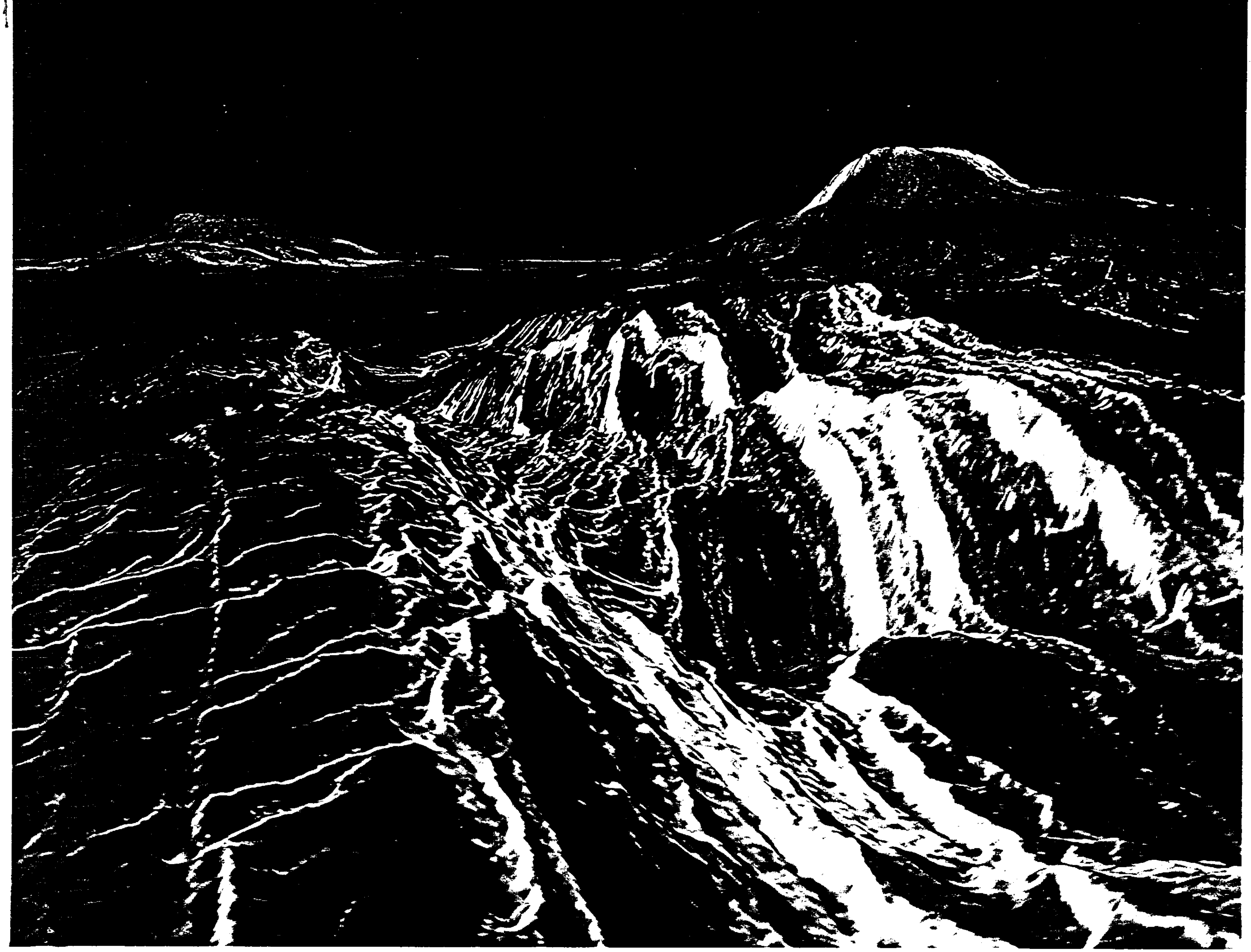

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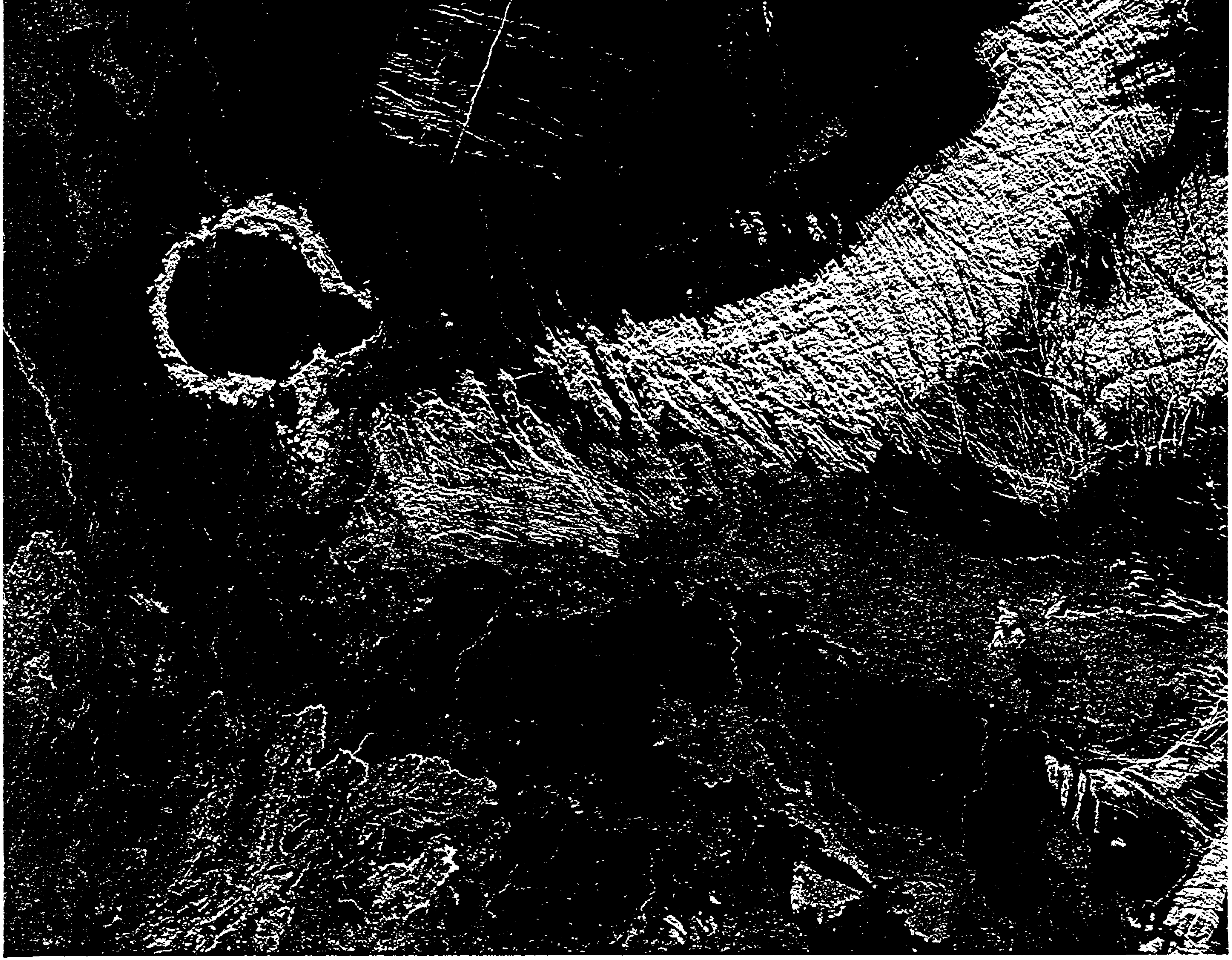

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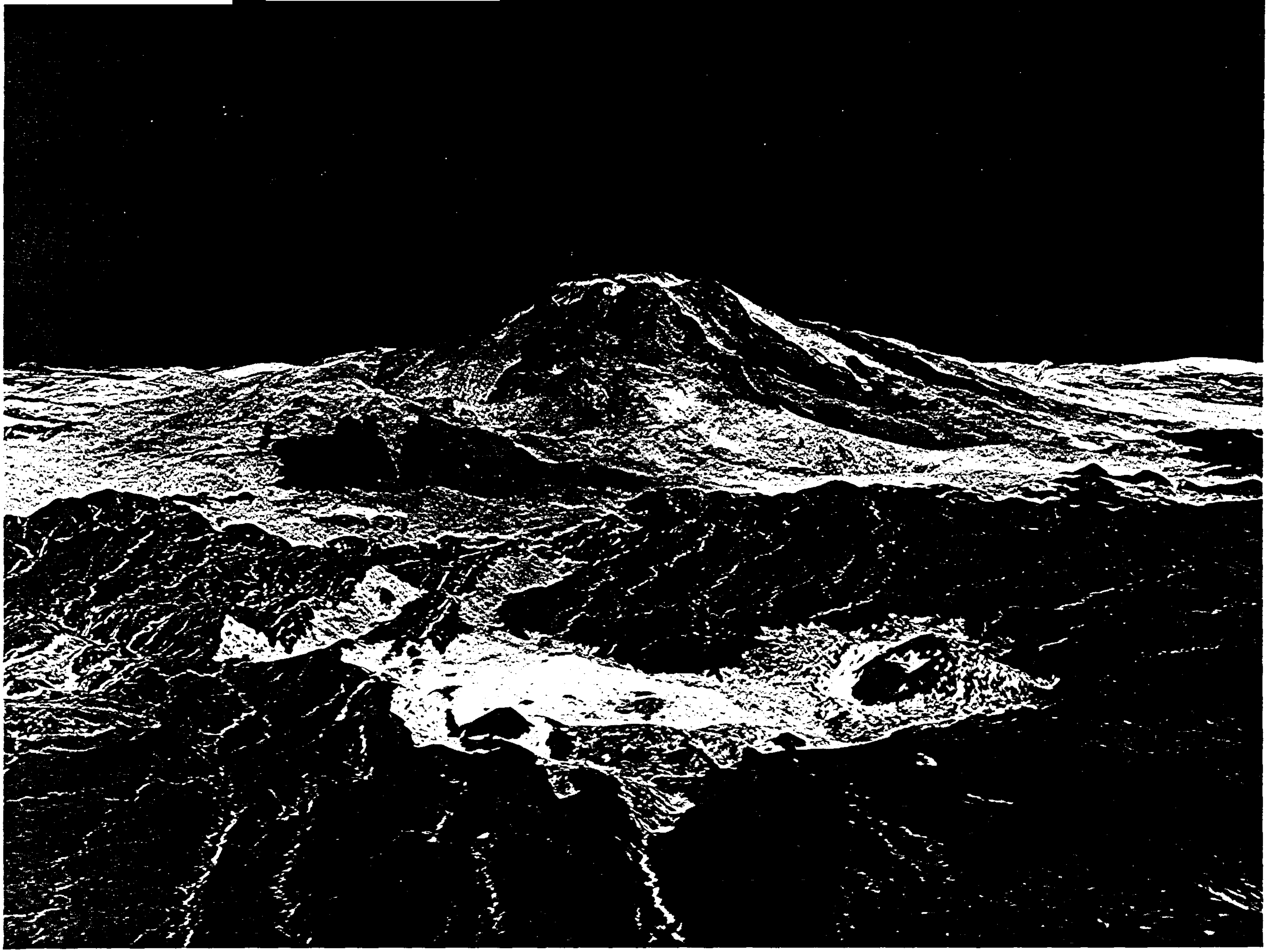

Figure 7 P-40175